Evidence for $H \rightarrow \ell^+\ell^-\gamma$ and searches for new physics involving photons with ATLAS

Anthony Morley
On behalf of the ATLAS collaboration
February 2nd 2021
Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS - Anthony Morley

- The force carrier you can literally see
Evidence for $H \rightarrow \ell^+ \ell^-$ and searches for new physics involving photons with ATLAS - Anthony Morley

Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS - Anthony Morley
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High mass $\gamma \gamma$ resonance

$H(\rightarrow \gamma \gamma)+\text{MET}$

$H \rightarrow \ell \ell \gamma$
Rough analysis procedure

Step 1

- Event and object selection, categorisation

Step 2

- Parameterisation of the final discriminate

Step 3

- Simultaneous fit to all categories via a likelihood
**Background parameterisation**

**Step 2.1**
- Create template for each contributing process

**Step 2.2**
- Add templates together to get a total background shape
- If needed: Smooth background to reduce stat. fluctuations

**Step 2.3**
- Parameterisation of the bkg. shape
- Estimate uncertainty associated with choice of the function
- Spurious Signal

Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS - Anthony Morley
• Resonances decaying to a pair of photons predicted by several BSM models

• Spin-0 and 2 search performed
  • Spin 0 (X)- narrow or large width resonance ($\Gamma_X / m_X = 10\%$)
  • Spin-2 (G*)- RS graviton $0.01 < k/M_{pl} < 0.1$

• Search for peak in the diphoton mass spectrum
Event selection

- Analysis selections targeting both Spin-0 and Spin-2
- Data recorded with diphoton triggers
  - $E_T(\gamma_1) > 35$ GeV, $E_T(\gamma_2) > 25$ GeV
- Final selection:
  - $E_T(\gamma_1) > 40$ GeV, $E_T(\gamma_2) > 30$ GeV
  - $|\eta(\gamma)| < 2.37$, excluding crack region
  - Tight Isolation and Tight Photon ID
  - Relative $E_T: E_T(\gamma_1)/m_{\gamma\gamma} > 0.3$, $E_T(\gamma_2)/m_{\gamma\gamma} > 0.25$
  - $m_{\gamma\gamma} > 150$ GeV
- Signal Eff.: 53% (Spin-0), 42% (spin-2) @ 1 TeV

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Signal modelling

- Detector resolution effects: Double sided Crystal Ball (DSCB)
  - Linear parameterisation of DSCB as function of mass

- Resolution:
  - Spin 0/2 ~0.6% $m_{\gamma\gamma}$ @ 2TeV

- DSCB is convolved with signal line shape
  - Spin 0: relativistic Breit-Wigner
  - Spin 2: graviton line-shape

![Graph showing signal modelling results](image)
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**Background modelling**

- Background template
  - $\gamma\gamma$ MC based
  - $\gamma+$jet & jet+jet data driven

- Components added according to measured fraction ($\gamma\gamma=0.92$, $\gamma+$jet=0.08)
  - estimated with using a isolation and ID sideband decomposition (2x2D decomposition)

- Smooth background templates- Functional Decomposition
  - Reduces statistical fluctuations in template

- Select a parametric function:
  $$f_b(x; \{\alpha, \alpha_i\}) = (1 - x^{1/3})^a \cdot x^\alpha_0 + \alpha_1 \cdot \log(x)$$
  - Function able to accommodate all systematic variations

![Graph showing $dN/dm_{\gamma\gamma}$ and $\gamma\gamma$ fraction vs $m_{\gamma\gamma}$](image)
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Dominant Systematic Uncertainties

- Signal yield
- Production mode
- Signal modeling
- Photon energy resolution
- Background model
- Bias on signal yield estimation from background mismodeling, quantified by the extracted signal yield when fitting the background template with S+B model.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>±1.7%</td>
</tr>
<tr>
<td>Photon identification</td>
<td>±0.5%</td>
</tr>
<tr>
<td>Photon energy scale/resolution</td>
<td>negligible</td>
</tr>
<tr>
<td>Spin-0 production process*</td>
<td>± (7–3) %</td>
</tr>
<tr>
<td>Trigger</td>
<td>±0.5%</td>
</tr>
<tr>
<td>Photon isolation</td>
<td>±1.5%</td>
</tr>
<tr>
<td>Pile-up reweighting*</td>
<td>± (2–0.2) %</td>
</tr>
<tr>
<td>Background model</td>
<td></td>
</tr>
<tr>
<td>Bias on signal yield estimation from S+B</td>
<td></td>
</tr>
<tr>
<td>model</td>
<td></td>
</tr>
</tbody>
</table>

Spurious signal, Spin-0:

- NWA: 114–0.04 events ($m_X = 160–2800$ GeV)
- $\Gamma_X/m_X = 2\%$: 107–0.14 events ($m_X = 400–2800$ GeV)
- $\Gamma_X/m_X = 6\%$: 223–0.38 events ($m_X = 400–2800$ GeV)
- $\Gamma_X/m_X = 10\%$: 437–0.50 events ($m_X = 400–2800$ GeV)

Spurious signal, Spin-2:

- $k/M_B = 0.01$: 4.71–0.04 events ($m_G = 500–2800$ GeV)
- $k/M_B = 0.05$: 19.0–0.09 events ($m_G = 500–2800$ GeV)
- $k/M_B = 0.1$: 31.2–0.20 events ($m_G = 500–2800$ GeV)

* mass-dependent
Full model and data

- A Likelihood is constructed from signal and background parametrisation
- Parametric function accurately models the shape
- Search new resonance by scanning parameter \((m_X, \Gamma_X)/(m_{G*}, k/M_{Pl})\)
- Mass scan range varies depending on the model
• Largest deviation: 3.3σ (local), 1.3σ (global) at $m_X = 684$ GeV
• Upper limits on the fiducial cross-section with NWA: 12.5 fb -> 0.03 fb.
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- Largest deviation: $3.3\sigma$ (local), $1.36\sigma$ (global) at $m_X = 684$ GeV
- Upper limits on the total cross-section with $k/M_{Pl}=0.1$: $3.2$ fb $\rightarrow 0.04$ fb.
The Higgs in 2021

- Entering the precision era for Higgs physics
- Higgs properties
- Differential XS measurement
- Searches for rare processes

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H(→γγ)+MET : Dark matter?

- Strong astrophysical evidence for Dark Matter
- Dark matter provides a clear empirical direction for physics beyond the Standard Model.
- We make the assumption that dark matter has particle-like nature
Dark matter searches at the LHC

- Searches for Dark matter at the LHC have taken on many forms
- Some of the most versatile are the Mono-X (X = jet, W, Z, γ)
  - X is produced from ISR
  - SM particle also provides something to trigger on
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Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS - Anthony Morley

- The Higgs boson is generally assumed to couple to a massive mediator in the model
- ISR Higgs boson production cross-section is negligible
- In this search $H(\rightarrow \gamma \gamma) + E_T^{\text{miss}}$ three models are tested:

  - $Z'_B$
  - $Z'_{2\text{HDM}}$
  - $2\text{HDM}+a$
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### Event selection

- **Data recorded with diphoton triggers**
  - $p_T(\gamma_1) > 35$ GeV, $p_T(\gamma_2) > 25$ GeV

- **Photons**
  - $p_T(\gamma) > 25$ GeV
  - $|\eta(\gamma)| < 2.37$, excluding crack region
  - Tight Isolation and Tight Photon ID
  - Relative $E_T$: $E_T(\gamma_1)/m_{\gamma\gamma} > 0.35$, $E_T(\gamma_2)/m_{\gamma\gamma} > 0.25$

- **Jets**: AntiKt(R=0.4) Particle flow
  - $p_T(\text{jet}) > 25$ GeV, $|\eta(\text{jet})| < 4.4$

- **Electron and Muons**
  - $p_T(\gamma) > 10$ GeV
  - $|\eta(\gamma)| < 2.47$

- **Final Requirements**
  - 2 photons, No leptons, $E_T^{\text{miss}} > 90$ GeV, $\Delta E_T^{\text{miss}} < 30$ GeV
  - $105$ GeV $< m_{\gamma\gamma} < 160$ GeV
  - Acceptance varies significantly depending on the model

### Diagram Description

- **Data**
  - SM Higgs Boson
  - $V\gamma$
  - $V\gamma$

- **Models**
  - $Z2HDM$, $m_z = 800$ GeV, $m_A = 500$ GeV
  - $ZB$, $m_z = 1000$ GeV, $m_z = 50$ GeV
  - $2HDM+a$, $\tan\beta=1$, $\sin\theta=0.7$, $m_A = 300$ GeV, $m_h = 250$ GeV
  - $2HDM+a$, $\tan\beta=1$, $\sin\theta=0.35$, $m_A = 600$ GeV, $m_h = 200$ GeV
Event categorisation

- Events are then divided into 4 signal regions based on $E_T^{\text{miss}}$ and BDT score
- A BDT trained using $p_T(\gamma\gamma)$ and MET Significance as inputs
  - Signal: a single 2HDM+a signal point
  - Background: control region with loose or non-isolated photons
  - Significant gains in expected sensitivity over solely cut based analysis
Event categorisation

- BDT cuts out rather particular regions of phase space

<table>
<thead>
<tr>
<th>Category</th>
<th>$E_T^{\text{miss}}$ cut</th>
<th>BDT score cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>High $E_T^{\text{miss}}$ BDT tight</td>
<td>$E_T^{\text{miss}} &gt; 150$ GeV</td>
<td>$0.950 &lt; $BDT score $&lt; 1$</td>
</tr>
<tr>
<td>High $E_T^{\text{miss}}$ BDT loose</td>
<td>$E_T^{\text{miss}} &gt; 150$ GeV</td>
<td>$0.694 &lt; $BDT score $&lt; 0.950$</td>
</tr>
<tr>
<td>Low $E_T^{\text{miss}}$ BDT tight</td>
<td>$E_T^{\text{miss}} &lt; 150$ GeV</td>
<td>$0.864 &lt; $BDT score $&lt; 1$</td>
</tr>
<tr>
<td>Low $E_T^{\text{miss}}$ BDT loose</td>
<td>$E_T^{\text{miss}} &lt; 150$ GeV</td>
<td>$0.386 &lt; $BDT score $&lt; 0.864$</td>
</tr>
</tbody>
</table>
Signal and background modelling

- Final discriminate is the $m_{\gamma\gamma}$ spectrum.
- Signal & Resonant background (SM Higgs production)
  - DSCB is used to parameterise the shape
  - Parameterised separately for BSM and SM.
- Non-Resonant Background
  - $m_{\gamma\gamma}$ template constructed from:
    - $\gamma\gamma$-shape based on MC ($\gamma\gamma$, $\gamma\gamma+V\gamma$)
    - $\gamma$-jet shape data driven
  - Data driven purity estimate
    - using a isolation and ID sideband decomposition (2x2D decomposition)
    - $\gamma\gamma$, 80% $\gamma$-jet 18%, jet-jet 2%
  - Function selected that is able to parameterise the expected $m_{\gamma\gamma}$ spectrum
    - An exponential is used for all categories

<table>
<thead>
<tr>
<th>Category</th>
<th>$\Delta N_{\text{bkg model}}^{\text{sig}}$</th>
<th>$\Delta N_{\text{bkg model}}^{\text{sig}}/N_{\text{bkg}}^{\text{non-res.}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High $E_T^{\text{miss}}$ BDT tight</td>
<td>0.54</td>
<td>6.8</td>
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<tr>
<td>High $E_T^{\text{miss}}$ BDT loose</td>
<td>1.07</td>
<td>4.2</td>
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<tr>
<td>Low $E_T^{\text{miss}}$ BDT tight</td>
<td>0.62</td>
<td>6.3</td>
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<tr>
<td>Low $E_T^{\text{miss}}$ BDT loose</td>
<td>2.64</td>
<td>2.0</td>
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### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Signals [%]</th>
<th>Backgrounds [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SM Higgs boson</td>
</tr>
<tr>
<td>Experimental</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.7</td>
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<tr>
<td>Trigger efficiency</td>
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<td>1.0</td>
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<tr>
<td>Vertex selection (inclusive cat.)</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
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<td>Photon energy scale</td>
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<td>0.4</td>
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<tr>
<td>Photon identification efficiency</td>
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<td>1.3</td>
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<tr>
<td>Photon isolation efficiency</td>
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<td>1.4</td>
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<tr>
<td>ATLFASTII simulation</td>
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<td>-</td>
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<tr>
<td>$E_T^{miss}$ reconstruction and jet uncertainty</td>
<td>2.8</td>
<td>1.7</td>
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<tr>
<td>Pileup reweighting</td>
<td>2.3</td>
<td>2.0</td>
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<tr>
<td>Signal efficiency interpolation</td>
<td>&lt; 13</td>
<td>-</td>
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<tr>
<td>Non-resonant background modeling</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Theoretical</td>
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<td></td>
</tr>
<tr>
<td>Factorization and renormalization scale in migration</td>
<td>1.3</td>
<td>3.5</td>
</tr>
<tr>
<td>PDF+$\alpha_S$ in migration</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Multi-parton interactions, ISR/FSR, hadronization</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>$B(H \rightarrow \gamma\gamma)$</td>
<td>1.73</td>
<td>1.73</td>
</tr>
</tbody>
</table>
Results

- No excess w.r.t. total background

- Some SM Higgs background is expected
Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS

- Limits on $m_{Z'B}$ 1150 GeV for light Dark matter candidates
- Improves limits $m_\chi < 2$ GeV
- Factor of 2 better w.r.t. previous publication

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

Limits at 95% CL

$\sin\theta = 0.3$, $g_q = 1/3$, $g_\chi = 1$

$h(\gamma\gamma) + E_T^{\text{miss}}, Z'_{B}$, Dirac DM
Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS

- Complements other searches the limit $m_A \rightarrow m_a + m_h$
- Large portion of the possible mixings angles excluded for this benchmark point

ATLAS Preliminary

*Complements other searches the limit $m_A \rightarrow m_a + m_h$

*Large portion of the possible mixings angles excluded for this benchmark point*
- Very rare process
- Numerous processes contribute to the final state
- Diverse final state kinematics
  - Dedicated analyses for different regions of phase space.
- Some disagreement in literature in about the expected BR
- Used Pythia8 to estimate
  \[
  \mathcal{B}(H \rightarrow \ell\ell\gamma) \mid m_{\ell\ell}<30 \text{ GeV}:
  \]
  \[
  \mathcal{B}(H \rightarrow e\gamma) = 7.20 \times 10^{-5} \\
  \mathcal{B}(H \rightarrow \mu\gamma) = 3.42 \times 10^{-5}.
  \]
Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS - Anthony Morley

Previous measurements of $H \rightarrow \ell\ell\gamma$

- Run 1 and early Run 2 searches for $H \rightarrow \ell\ell\gamma$
  - all are statistically limited
  - all consistent with background only hypothesis

- Last year ATLAS published its results $H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$:
  - $\mu_{Z\gamma} = 2.0 \pm 0.9$ (stat) $+0.4/-0.3$ (syst)

- Today our first result for $H \rightarrow \ell\ell\gamma$ for $m_{\ell\ell} < 30$ GeV

95% confidence level upper limit

- Observed 3.9
- Expected (no Higgs) 2.0

$H \rightarrow Z\gamma \rightarrow \ell\ell\gamma$

95% confidence level upper limit

- Observed 3.6
- Expected (no Higgs) 1.7
Detector Signature

- Due to the low mass of the dilepton pair they are often very collimated
- Limited spacial resolution of the detector
  - Merged electron + Photon / 2 electrons + Photon
  - Not an issue for muons
• Can’t rely on regular single leptons triggers alone
  • single-ℓ, 2ℓ, γ–ℓ, γγ, γ–2ℓ

• Efficiency with respect to final selection
  • Muon channels: 96.2%
  • Resolved electron categories: 96.5%
  • Merged electron categories: 99.8%
Merged Electron Identification

- Largely look like converted to ee pairs early expect:
  - $m_{ee} \neq 0$, opening angle $\neq 0$, $\implies$ broader cluster

- Requires dedicated PID to ensure reasonable efficiency is maintained vs. angular separation.

- Cut based PID inputs:
  - Variables constructed from the tracks
    - Neutral vertex contracted from the 2 selected tracks
    - Cluster vertex and track matching requirement
  - Variables shower the EM shower shapes
    - Some of which are dependent on the properties of the tracks
  - Additional cuts are applied to reduce background from single electrons

![Graph showing merged ee ID efficiency]

\[ \text{Simulation Preliminary} \]

\[ \sqrt{s} = 13 \text{ TeV} \]

\[ H \rightarrow \gamma^* \gamma \rightarrow ee\gamma \]
Merged electron: Efficiency measurements

- Use Z→llγ events to perform efficiency measurements
  - Consider only converted photons, with conversion radius <160mm to have an object similar to γ*

- Extract efficiency of Merged ID + a tight isolation requirement
  - Fit to the ℓℓγ mass spectrum, with Z→ℓℓγ signal shape from MC and Z+jet background from inverted ID/isolation control regions

- Scale factors cross-checked using electrons from Z→ee
  - with Smirnov transformation to make each individual PID variable look as expected
Merged electron: Calibration

- A merged electron ($\gamma^*$) looks like photon conversions treat them as such
- Calibrate $\gamma^*$ as an early converted photon with radius 30mm
- The small differences taken as additional systematic uncertainty
Event selection

- Photons
  - $p_T > 20$ GeV
  - Tight ID
  - Loose Isolation

- Resolved Electrons:
  - $p_T > 4.5$ GeV
  - Medium ID
  - Loose isolation applied only to the leading e

- Merged Electrons
  - $p_T > 20$ GeV
  - Custom ID
  - Tight Isolation

- Muons:
  - $p_T > 3.0$ GeV
  - Medium ID
  - Track isolation applied only to leading $\mu$

- Jets:
  - $p_T > 20$ GeV
  - AntiKt(R=0.4) Particle Flow

- Final selection:
  - Require event to have with 2 leptons and photon
  - $m_{\ell\ell} < 30$ GeV
  - Veto $J/\psi$ and $Y(nS)$ mass range
  - $105$ GeV $< m_{\ell\ell\gamma} < 160$ GeV
  - Relative $p_T$: $p_T(\ell\ell)/m_{\ell\ell}$ $> 0.3$, $p_T(\gamma)/m_{\ell\ell\gamma}$ $> 0.3$
  - Signal Efficiency: $\mu\mu\gamma \sim 28\%$, $ee\gamma \sim 14\%$
Categorisation

- For each signature 3 kinematic categories are created
  - VBF-enriched
    - 2 jets $p_T > 25$ GeV ($>30$ GeV if $|\eta_{\text{jet}}| > 2.5$)
    - $m_{jj} > 500$ GeV, $\Delta\eta_{jj} > 2.7$, $\Delta\eta_{\text{Zepp}} < 2.0$
    - $\Delta\phi(\ell\ell\gamma,jj) > 2.8$
    - $\Delta R(\text{obj},j) > 1.5$ for the leading 2 jets and obj = $\gamma,\ell_1,\ell_2$
  - High-$p_T$-Thrust
    - $!\text{VBF-enriched}$ & $p_T$-Thrust($\ell\ell\gamma) > 100$ GeV
  - Low-$p_T$-Thrust
    - Everything else

- Discriminating variables inspired by $H \rightarrow \gamma\gamma$ analysis (very similar signal topology)
Signal Modelling

- Analysis strategy: use a S+B fit to the $m_{\ell\ell\gamma}$ distribution in the range [110,160] GeV, in each category (simultaneous fit in all categories)
- Use a DSCB function to model the signal in each individual channel
  - Effective resolution between 1.6 and 2.2 GeV
- Highly suppressed resonant background from $H \rightarrow \gamma\gamma$ parametrised using the same functional form
  - Yield from MC based on measured $\sigma \times B(H \rightarrow \gamma\gamma)$ (Phys. Rev. D 98, 052005)
  - At most a few % of the expected signal in any category
Background modelling

- Background modelled using a parametric function
  - Function choice based on expected background shape

- Composition - Isolation Template method
  - Using isolation templates, derived in a region with inverted ID, and then normalised in the high-isolation tail

- Fraction of events with jets faking:
  - $\gamma$: 6–11% (category dependent)
  - $\mu$: 4–15%
  - $e$: 2–27%
**Background templates**

- **Background Template:**
  - Use MC (LO Sherpa 2.2) \(\ell\ell\gamma\) to model the irreducible \(\ell\ell\gamma\) background
  - Reweight this generator-level sample to account for reconstruction-level effects
  - Obtain shapes for fake backgrounds in data control regions
  - Components added together with measured compositions
Background modelling

- Background function choice
  - S+B fit to expected background
  - Functions must model the expected background with a reasonable $\chi^2$ probability
  - Functions with low bias and with low degrees of freedom are preferred

<table>
<thead>
<tr>
<th>Channel</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu$ VBF-enriched</td>
<td>$m^\alpha$</td>
</tr>
<tr>
<td>$\mu\mu$ High-$p_T$-Thr</td>
<td>$m^\alpha$</td>
</tr>
<tr>
<td>$\mu\mu$ Low-$p_T$-Thr</td>
<td>$e^{\alpha m + \beta m \times m}$</td>
</tr>
<tr>
<td>Merged e VBF-enriched</td>
<td>$m^\alpha$</td>
</tr>
<tr>
<td>Merged e High-$p_T$-Thr</td>
<td>$m^\alpha$</td>
</tr>
<tr>
<td>Merged e Low-$p_T$-Thr</td>
<td>$e^{\alpha m + \beta m \times m}$</td>
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<tr>
<td>Resolved e VBF-enriched</td>
<td>$e^{\alpha m}$</td>
</tr>
<tr>
<td>Resolved e High-$p_T$-Thr</td>
<td>$m^\alpha$</td>
</tr>
<tr>
<td>Resolved e Low-$p_T$-Thr</td>
<td>$m^\alpha$</td>
</tr>
</tbody>
</table>
Systematics

- Analysis is statistically limited
- Leading experimental systematics
  - background modelling uncertainty
  - lepton efficiency/resolutions
- Theoretical uncertainty
  - Branching ratio
  - QCD scale

<table>
<thead>
<tr>
<th>Source</th>
<th>( \mu )</th>
<th>( \sigma \times B )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spurious Signal</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>( \mathcal{B}(H \rightarrow \ell\ell\gamma) )</td>
<td>5.8</td>
<td>–</td>
</tr>
<tr>
<td>QCD</td>
<td>4.7</td>
<td>1.1</td>
</tr>
<tr>
<td>( \ell, \gamma, ) jets</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>PDF</td>
<td>2.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Pile-up</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Minor prod. modes</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow \gamma\gamma ) bkg</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Parton Shower</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Total systematic</td>
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<td>7.9</td>
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</table>

Uncertainty measured values [%]
Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS

**Results**

- **Observed:**
  \[
  \mu = 1.5 \pm 0.5 = 1.5 \pm 0.5 \text{ (stat.)} \pm 0.2 \text{ (syst.)}
  \]

- **Cross Section**
  \[
  \sigma \times \text{BR}(\ell \ell \gamma) \big|_{m\ell\ell<30 \text{ GeV}}: \quad 8.7 \pm 2.8 \text{ fb} = 8.7 \pm 2.7 \text{ (stat.)} \pm 0.7 \text{ (syst.)} \text{ fb}
  \]
Results

• Significance above background-only hypothesis: 3.2σ (expected 2.1σ)

• First evidence for $H \rightarrow \ell\ell\gamma$
Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS - Anthony Morley

Internal consistency of results

- Good consistency between all measured channels

<table>
<thead>
<tr>
<th>Category</th>
<th>Measured $(\sigma \cdot B)/ (\sigma \cdot B)_\text{SM}$</th>
<th>Uncertainty</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td></td>
<td></td>
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</table>

H → $\gamma^* \gamma \rightarrow ll\gamma$ global fit

$\sigma \cdot B/(\sigma \cdot B)_\text{SM}$

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

- Total unc.
- Syst. only

Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS - Anthony Morley
Summary

- Photons — a versatile tool for physics
- Improved analysis techniques always being developed
  - Function decompositions, MVA categorisations, Improved ID, Merged electrons
- Improved limits on $X/G^* \rightarrow \gamma\gamma$ & $H(\rightarrow \gamma\gamma) + E_T^{\text{Miss}}$
- First evidence for $H \rightarrow \ell\ell\gamma$
  - $m_{\ell\ell} < 30$ GeV : $3.2\sigma$, $\mu = 1.5 \pm 0.5$
  - Looking forward to more data to study this process in more detail
Additional Information
Useful links

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ResultswithData2018
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS - Anthony Morley

ATLAS EM cluster shower shapes

$$f_1 = \frac{E_{S_1}}{E_{\text{tot}}}$$

$$f_{\text{side}} = \frac{E_{S_1} - E_{S_3}}{E_{S_1}}$$

$$R_\eta = \frac{E_{S_2}}{E_{S_2}^{\eta \times 7}}$$

$$R_\phi = \frac{E_{S_2}}{E_{S_2}^{\phi \times 7}}$$

$$R_{\text{had}} = \frac{E_{\text{had}}^{\text{S} \times \text{S}_1}}{E_{\text{T}}^{\text{S} \times \text{S}_1}}$$

$$w_{\eta_2} = \sqrt{\frac{\Sigma E_i \eta_i^2}{\Sigma E_i} - \left( \frac{\Sigma E_i \eta_i}{\Sigma E_i} \right)^2}$$

width in a $3 \times 5$ ($\Delta \eta \times \Delta \phi$) region of cells in $S_2$

$$w_s = \sqrt{\frac{\Sigma E_i (i - i_{\text{max}})^2}{\Sigma E_i}}$$

$w_{s,3}$ uses $3 \times 2$ strips ($\eta \times \phi$)

$w_{s,\text{tot}}$ is defined similarly but uses $20 \times 2$ strips

$$\Delta E = E_{\text{max},2}^{S_1} - E_{\text{min}}^{S_1}$$

$$E_{\text{ratio}} = \frac{E_{\text{max},1}^{S_1} - E_{\text{max},2}^{S_1}}{E_{\text{max},1}^{S_1} + E_{\text{max},2}^{S_1}}$$
Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS - Anthony Morley
Functional Decomposition

- An template is formed by taking Sherpa MC γγ events and fitting with series of basis functions, $E_n(z)$.
- Best-fit hyperparameters $\alpha, \lambda$ ($m_0 = 150$ GeV) are determined by maximizing the marginal likelihood.
- After templates formed, S+B fit applied to the templates. Systematic variations provide separate templates and spurious signal systematic determined from maximum envelope of $|N_{SS}|$.

$z(m) = \left(\frac{m-m_0}{\lambda}\right)^\alpha$

$F_n(z) = \sqrt{2} \ e^{-nz}$

$E_n(z) = \sum_{m=0}^{n} d_{nm} F_m(z)$
Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS - Anthony Morley

2x2D background estimate

- Data-driven method to estimate the diphoton purity
- Irreducible background $\gamma\gamma$, $V\gamma\gamma$ + $V\gamma$ and reducible background $j\gamma$, $\gamma j$, $jj$
- By fitting the fraction of the contribution of the different components in the 16 categories the purity can be obtained

\[
N_{AA}^{all} = N_{AA}^{\gamma\gamma} + N_{AA}^{\gamma j} + N_{AA}^{j\gamma} + N_{AA}^{jj}
\]
Evidence for $H \rightarrow \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS - Anthony Morley
Evidence for $H \rightarrow \ell^+\ell^-\gamma$ and searches for new physics involving photons with ATLAS

**H($\rightarrow\gamma\gamma$)+MET: Event yield**

$120$ GeV $< m_{\gamma\gamma} < 130$ GeV

<table>
<thead>
<tr>
<th>Category</th>
<th>High $E_T^{\text{miss}}$ BDT tight</th>
<th>High $E_T^{\text{miss}}$ BDT loose</th>
<th>Low $E_T^{\text{miss}}$ BDT tight</th>
<th>Low $E_T^{\text{miss}}$ BDT loose</th>
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<tbody>
<tr>
<td>Data</td>
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<td>29</td>
<td>11</td>
<td>143</td>
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<tr>
<td><strong>Backgrounds</strong></td>
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<tr>
<td>SM Higgs boson</td>
<td>$3.74 \pm 0.25$</td>
<td>$3.40 \pm 0.28$</td>
<td>$3.12 \pm 0.23$</td>
<td>$9.9 \pm 1.5$</td>
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<tr>
<td>Non-resonant</td>
<td>$7.8 \pm 1.3$</td>
<td>$25.3 \pm 2.3$</td>
<td>$9.8 \pm 1.5$</td>
<td>$130 \pm 5$</td>
</tr>
<tr>
<td>Total</td>
<td>$11.6 \pm 1.3$</td>
<td>$28.7 \pm 2.3$</td>
<td>$12.9 \pm 1.5$</td>
<td>$140 \pm 5$</td>
</tr>
</tbody>
</table>

$Z'_B$ model, $m_{Z'_B} = 1000$ GeV, $m_\chi = 50$ GeV

| Signal yields    | $0.7 \pm 3.1$                       | $0.1 \pm 0.6$                       | $0.1 \pm 0.6$                     | $0.1 \pm 0.6$                     |

$Z'$-2HDM model, $m_A = 800$ GeV and $m_\chi = 500$ GeV

| Signal yields    | $0.6 \pm 3.1$                       | $0.1 \pm 0.4$                       | $0.05 \pm 0.26$                   | $0.03 \pm 0.17$                   |

2HDM+a model, $m_A = 600$ GeV, $m_a = 200$ GeV, $\tan \beta = 1.0$, $\sin \theta = 0.35$

| Signal yields    | $0.6 \pm 3.1$                       | $0.2 \pm 1.2$                       | $0.1 \pm 0.5$                     | $0.1 \pm 0.7$                     |
Evidence for $H \to \ell^+ \ell^- \gamma$ and searches for new physics involving photons with ATLAS - Anthony Morley
Evidence for H→ℓ⁺ℓ⁻γ and searches for new physics involving photons with ATLAS - Anthony Morley

2HDM+a